DECAYING COLD DARK MATTER MODEL AND SMALL-SCALE POWER

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ABSTRACT

The canonical cold dark matter (CDM) model with a cosmological constant (ΛCDM) apparently possesses too much small-scale ($l \sim 1 - 100\,$kpc) power at $z = 0$, manifested as over-concentration of dark matter in inner regions of galaxies and over-abundance of dwarf galaxies. We suggest an alternative, ΛCDM based model in which one half of the CDM particles have decayed into relativistic particles by $z = 0$. This model, called ΛDCDM, successfully lowers the concentration of dark matter in dwarf galaxies as well as in large galaxies like our own *at low redshift*, while simultaneously retaining the many successes of the ΛCDM model at high redshift. At the same time, this model solves the problem of over-production of small dwarf galaxies in the ΛCDM *not by removing them but by identifying them with failed, "dark" galaxies*, where star-formation is quenched due to dark matter evaporation and consequently halo expansion.

A COBE-and-cluster normalized ΛDCDM model can be constructed with the following parameters: $H_0 = 60$km/sec/Mpc, $\lambda_0 = 0.60$, $\Omega_{0,CDM} = 0.234$, $\Omega_{0,b} = 0.044$, $n = 1.08$, and $\sigma_8 = 1.00$. A noted effect from CDM decay is a shift of the first Doppler peak in the Cosmic Microwave Background angular power spectrum to a larger scale, since the non-relativistic matter density parameter is higher at high redshift ($\Omega_{i,NR} = 0.512$). With the adopted parameters the model produces the location of the first Doppler peak in accord with the recent BOOMERANG result. Some other features of the model are also discussed.

A clean test of this model can be made by measuring the evolution of gas fraction in clusters. The prediction is that the gas fraction should decrease with redshift and is smaller by 31% at $z = 1$ than at $z = 0$. X-ray and Sunyaev-Zel'dovich effect observations should provide such a test.

Subject headings: Cosmology: cosmic microwave background – cosmology: dark matter – cosmology: large-scale structure of Universe – cosmology: theory – galaxies: formation

1. INTRODUCTION

While the canonical ΛCDM model is remarkably successful in many ways (Ostriker & Steinhardt 1995; Bahcall et al. 1999), there is now some evidence that it may have too much power on small scales ($l \sim 1 - 100\,$kpc) today. Evidence includes a large excess of dwarf galaxies (Klypin et al. 1999; Moore et al. 1999), the over-concentration of dark matter in dwarf galaxies (Moore 1994; Flores & Primack 1994; Burkert 1995; McGaugh & de Blok 1998; Moore et al. 1999) as well as in large galaxies (Navarro & Steinmetz 2000). Without impairing the many notable virtues of the ΛCDM model, in this *Letter* we suggest a ΛCDM model in which one half of the CDM particles decay into relativistic particles by $z = 0$.

2. DECAYING COLD DARK MATTER MODEL

Decaying CDM was suggested earlier in attempts to save the CDM model in an Einstein-de Sitter universe (Turner, Steigman, & Krauss 1984; Doroshkevich & Khlopov 1984; Olive, Seckel, & Vishniac 1985). Suggestions were also made in the context of neutrino models for similar rescue missions (Davis et al. 1981; Hut & White 1984).

To illustrate the effect of CDM decay, we show how the profile of a halo would be altered. Suppose a pure CDM halo formed by some high redshift z_{halo} has an NFW density profile

$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_c)(1 + r/r_c)^2}, \quad (1)$$

with an initial concentration parameter $c_i \equiv r_{200,i}/r_{c,i}$, where r_{200} is the radius within which the mean density is $200\rho_{crit}$ (ρ_{crit} is the critical density), and r_c is the characteristic "core" radius. Suppose that a fraction, $1 - y$, of the CDM particles will decay by $z = 0$. Since the proposed decay lifetime τ is greater than t_0 (the current age of the universe) and the orbital periods of particles inside r_{200} for halos of interest (sub-galactic, galactic and cluster types), one may assume that the change in the potential of the halo due to CDM decay is gradual, and the halo will expand in an adiabatic fashion. For this illustrative example we also assume that the halo maintains the NFW profile during expansion. We identify the "initial" (subscript "i") halo configuration with the halo configuration at $z = 0$ in the canonical ΛCDM model, where CDM particles are stable, and the "final" (subscript "f") halo configuration with the halo configuration at $z = 0$ in the ΛCDM model. Using virial theorem it can be shown that a particle at initial radius r_i will move out to r_f: $r_f = r_i/y$. The final "core" radius is therefore

$$r_{c,f} = r_{c,i}/y. \quad (2)$$

The mass inside $r_{200,i}/y$ is $yM_{200,i}$ by $z = 0$, where $M_{200,i}$ is the initial mass within $r_{200,i}$, and the final density within $r_{200,i}/y$ is $y^4\rho_{200}$. Defining $-\alpha$ as the effective slope of the

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density profile at $\sim r_{200}$, we obtain r_{200} approximately

$$r_{200,f} \approx y^{4/\alpha-1} r_{200,i}. \tag{3}$$

Another way to obtain $r_{200,f}$ is to use equation (1) directly to solve for r' within which the initial density is $200y^{-4}\rho_{crit}$. The resulting equation is $w(1+c_i w)^2 = y^4(1+c_i)^2$, where $w = r'/r_{200,i}$. Using $y = 0.5$ and $c_i = 30$ one obtains $w = 0.384$, resulting in the final virial radius $r_{200,f} = 0.384y^{-1}r_{200,i} = 0.77r_{200,i}$ (for $y = 0.5$), which is what equation (4) gives with $\alpha = 2.9$ (consistent with the known slope of halos near r_{200}). For our present purpose, we will simply adopt $\alpha = 3$ and use the analytic form of equation (3) for subsequent analyses. Combining equations (2,3) yields,

$$c_f = y^{4/\alpha} c_i. \tag{4}$$

For $y = 0.5$, it says $c_i/c_f = 2.5$. The circular velocity due to the CDM halo is (Navarro et al. 1997)

$$\left[\frac{V_c(r)}{V_{200}}\right]^2 = \frac{1}{x}\frac{\ln(1+cx) - (cx)/(1+cx)}{\ln(1+c) - c/(1+c)}, \tag{5}$$

where $x \equiv r/r_{200} = r/cr_c$. $V_{200,f}$ and $V_{200,i}$ are related:

$$V_{200,f} = y^{4/\alpha-1} V_{200,i} \tag{6}$$

Figure (1) shows rotation curves and mass profiles for the initial and final halos (with $y = 0.5$). The reduction in V_{max}, c and mass of the halo, and the increase in r_{max} in the ΛDCDM model should alleviate the density profile/concentration crisis. For example, the CDM mass within the solar circle ($\sim 0.1r_{200}$) will be reduced by a factor about 3.5, as seen in Figure 1. But for Milky Way like galaxies where CDM mass is not dominant today within the relevant radius, the reduction should be smaller, likely in the range $2-3$, which will bring the model into agreement with observations (Navarro & Steinmetz 2000). Detailed simulations including other important effects such as mergers and tidal fields should provide a more precise anwser. The effect of the decay of CDM particles on the abundance of small dwarf galaxies is also favorable. This, and additional attractive features as well as potential tests of the model, will be discussed in the next section.

3. DISCUSSION

3.1. *A Fiducial* ΛDCDM Model

Let us construct a fiducial ΛDCDM model based on the canonical ΛCDM model (Ostriker & Steinhardt 1995). We use the following parameters: $\Omega_{0,CDM} = 0.234$ (CDM density at $z = 0$), $\lambda_0 = 0.60$, $\Omega_{0,b} = 0.044$ (baryonic density at $z = 0$), $\Omega_{0,r} = 0.122$ (relativistic matter density at $z = 0$) and $h \equiv H_0/100$km/sec/Mpc$= 0.60$. The assumption that one half of the CDM particles decay by $z = 0$ translates into an exponential decay lifetime $\tau \sim 1.44t_0$, where t_0 is the current age of the universe. At $z >> 1$ the total nonrelativistic matter density is $\rho_{i,NR} = 0.512(1+z)^3\rho_{crit}$, where ρ_{crit} is the critical density at $z = 0$.

The current age is $t_0 = 0.84H_0^{-1}$ in this model, equal to 13.9 Gyrs for $h = 0.60$. Following Eke et al. (1996) cluster normalization requires $\sigma_8 = (0.52 \pm 0.04)\Omega_{0,NR}^{-0.52+0.13\Omega_{0,NR}}$ for $\lambda_0 + \Omega_{0,M} = 1$, which gives $\sigma_8 = 1.01 \pm 0.08$. Strictly speaking this fitting formula does not apply to ΛDCDM models. But we expect the difference is smaller than the error bar. We do not have a code readily available to compute σ_8 for ΛDCDM models from COBE normalization. Instead we use the following approximation: $\sigma_8(\Lambda\text{DCDM}, \lambda_0 = 0.6) \approx \sigma_8(\Lambda\text{CDM}, \lambda_0 = 0.6)\frac{K_2(\Lambda\text{CDM},\lambda_0=0.6)}{K_2(\Lambda\text{DCDM},\lambda_0=0.6)}\frac{D_0(\Lambda\text{DCDM},\lambda_0=0.6)}{D_0(\Lambda\text{CDM},\lambda_0=0.6)}$, where K_2 is the correction to the quadrupole amplitude due to late Integrated Sachs-Wolfe (ISW) effect (Kofman & Starobinskii 1985), and D_0 is the linear growth factor. We use CMBfast of Seljak & Zaldarriaga to compute $\sigma_8(\Lambda\text{CDM}, \lambda_0 = 0.6)$ with Bunn & White's (1997) normalization and obtain $\sigma_8(\Lambda\text{DCDM}, \lambda_0 = 0.6) = 1.00$ for $n = 1.08$.

Initially, $\Gamma \equiv \Omega_M h = 0.33$, which is consistent at 1.5σ with the value of $\Gamma = 0.24 \pm 0.06$ derived from large-scale structure observations (Feldman, Kaiser, & Peacock 1994). Due to the late decay of density fluctuations, power will be transferred from small scales to large scales. This effect may render an effective Γ at $z = 0$ smaller than its initial value, more consistent with observations. The universal deceleration parameter q_0 is found to be -0.38 (compared to -0.40 in the corresponding Λ model), which is consistent with the observations of high-z SNe (Schmidt et al. 1998). The essential parameters of the model are summarized in Table (1), where we also list a high Ω_b model.

We do not attempt to identify the particle physics model for the decaying CDM with the designed properties, but possible candidates for them are heavy neutrinos that decay to light neutrinos plus majoron (Gelmini, Schramm, & Valle 1984), or supersymmetric models involving the nonradiative decay of the gravitino (Olive, Schramm, & Srednicki 1984). Finally, CDM decay epoch appears to present another cosmic coincidence, as does the cosmological constant. We would conjecture, as the risk of being overly speculative, that the two parameters may be related at a more fundamental level.

3.2. *On Cosmic Microwave Background (CMB)*

The BOOMERANG result (de Bernardis et al. 2000; BOOM hereafter) indicates that the location of the first Doppler peak is on a scale larger than previously thought, for which the ΛCDM model does not provide a good fit. The BOOM result requires (holding other things fixed) $\Omega_M h^2 \approx 0.2$ for ΛCDM model (White, Scott, & Pierpaoli 2000; Tegmark & Zaldarriaga 2000). The fiducial ΛDCDM model in §3.1 gives $\Omega_{i,NR}h^2 \approx 0.18$ thus provides a good fit to the data. A larger ($\sim 10-15\%$) ISW effect in the ΛDCDM model than in the ΛCDM model with the same λ_0 (Kofman & Starobinskii 1985) has the effect of lowering the Doppler peaks relative to the COBE quadrupole point, which may be beneficial since the first Doppler peak seen by BOOM appears somewhat lower than previously thought (White et al. 2000; Tegmark & Zaldarriaga 2000).

While the dwarfness of the second Doppler peak detected by the BOOM may be explained by novel ideas such as a delay of the recombination (Peebles, Seager, & Hu 2000), a more conventional solution is to raise $\Omega_b h^2$ to 0.024 (White et al. 2000; Tegmark & Zaldarriaga 2000), which is larger that predicted by the light element nucleosynthesis of $\Omega_b h^2 = 0.0190 \pm 0.0024$ (Tytler et al. 2000). We note, however, that the mean decrement in Lyα forest at $z \sim 2$ requires $\Omega_b h^2 > 0.21$ (Rauch et al. 1997).

3.3. *On Small Scales – Dwarf Galaxies, Low Surface Brightness Galaxies, Dark Galaxies*

In the ΛDCDM model CDM halos become less concentrated only at low redshift. It is tempting to conjecture that CDM dominated galaxies (mostly dwarf galaxies) at moderate redshift become the low surface brightness galaxies (LSBGs; Bothun et al. 1987; McGaugh 1992) in the local universe. We suggest that the moderate-redshift faint blue compact objects (FBOs; Koo 1986; Tyson 1988; Cowie et al. 1988) are CDM dominated dwarf galaxies undergoing initial starbursts at $z \sim 1.0$, and subsequently expand to become the LSBGs seen today. There are several pieces of observational data that together provide evidence consistent with this scenario. First, the number density of FBOs is consistent with local LSBGs (Babul & Ferguson 1996). Second, the surface brightness of the LSBGs is roughly about 1.4 magnitude (i.e., a factor of 4.4) dimmer than HSBGs (McGaugh 1994), which is consistent with the expectation that FBOs have high surface brightness, and the expansion of size by a factor of ~ 2 just gives the indicated magnitude difference. Third, the LSBGs are weakly clustered (Mo, McGaugh, & Bothun 1994), in agreement with FBOs (Efstathiou et al. 1991); since galaxy clustering is not expected to involve rapidly from $z = 1$ to $z = 0$ (Katz, Hernquist, & Weinberg 1999; Cen & Ostriker 2000), the comparison between objects at $z \sim 1$ (FBOs) and at $z = 0$ (LSBGs) is indicative.

While the connection between FBOs and LSBGs was previously made by McGaugh (1994), there is a major difference between his proposal and ours. While he argues that FBOs are LSBGs at high z, we require that FBOs be HSBGs at high z, which subsequently evolve to LSBGs. There is some indication that our picture is in better agreement with recent HST observations (Glazebrook et al. 2000). Furthermore, our picture for moderate-redshift FBOs as HSBGs is more natural, for FBOs are thought to experience rather strong initial starbursts (Lacey & Silk 1991; Babul & Rees 1992; Gardner et al. 1993; Lacey et al. 1993; Kauffmann et al. 1994); local LSBGs are not starburst galaxies. Babul & Ferguson (1996) have also made the connection between FBOs and LSBGs based on detailed modeling of the star formation history of FBOs. The major difference between our model and theirs is that we do not require gas to be expelled from FBOs. It is noted that LSBGs are rather gas rich, *not gas poor*, and many LSBGs are fairly massive systems, for which it seems unlikely that gas can be easily driven out.

We would go further to propose that there exist two additional classes of some more numerous, (on average) lower mass CDM halos: ultra-low surface brightness galaxies (ULSBGs; Impey & Bothun 1997), and "dark" galaxies (DGs). ULSBGs have lower star formation rate than LSBGs, whereas DGs were never given a chance to form a significant amount of stars and were expanded away to remain dark. The existence of a sharp drop-off of star formation rate at a seemingly robust cut-off density (Kennicutt 1998) bodes well for this picture. Most of the excess number of dwarf halos found in N-body simulations of the ΛCDM model will now be ULSBGs and DGs in the ΛDCDM model. ULSBGs and DGs as well as LSBGs should be low in metallicity and rich in gas. It is intriguing that the nearby high velocity clouds (HVCs; Blitz et al. 1999), if confirmed to be extragalactic, may be DGs.

Peebles (1999) has repeatedly reminded us of a potential problem with CDM based models: Why are there not many dwarf galaxies with escape velocities greater than ~ 20km/sec in the voids, which are expected to form from low σ density peaks at low redshift? One answer born out in our picture is that the universe today may be filled with numerous LSBGs, ULSBGs, and DGs in voids (as well as in some other regions). The fact that low σ small-scale density peaks are more affected by the modulation by large-scale waves, which determine the large-scale structures such as voids and clusters, implies that low σ peaks virialize later in the voids than their counterparts in higher density environments; it may be that FBOs never formed in voids because of halo expansion. This effect may have left the voids filled with only ULSBGs and DGs, as observations do not seem to find any significant excess of LSBGs in voids (Schombert, Pildis, & Eder 1997).

3.4. *Other Implications of the* ΛDCDM Model

1. The combination of lower non-relativistic matter density at $z = 0$ (thus a higher σ_8 due to cluster normalization), a slower (about 25%) linear growth factor, a higher effective Γ at high redshift and higher non-relativistic matter density at high redshift dictates that ΛDCDM model has more power on all scales at high redshift compared to the corresponding ΛCDM model. This may prove to be attractive in light of the discovery of very high redshift, very luminous quasars (Fan et al. 2000). On larger scales, it appears that the canonical ΛCDM model underpredicts the abundance of high temperature clusters at $z \sim 0.83$ by a factor of about ten (see Figure 1 of Bahcall & Fan 1998). The ΛDCDM should have more high-z clusters but detailed simulations are needed to quantify this.

2. Galaxies at high redshift ($z \geq 1.0 - 2.0$) is expected to be smaller, on average, than local ones. In particular, there should be an excess number of small galaxies at $z \geq 1.0 - 2.0$, which may have already been seen in the Hubble Deep Field (e.g., Giallongo et al. 2000). But this effect is complicated by other processes including mergers.

3. The comoving distance to any redshift is shorter in the ΛDCDM model than in the corresponding ΛCDM model, which lessens the constraint on λ_0 imposed by gravitational lensing of galaxies (Kochanek 1996).

4. ULSBGs and DGs may make a sizable contribution to the number of Lyman alpha clouds and Lyman limit systems at low redshift and they are likely to cluster around large galaxies. They could provide the source of the "Type 1" population of Lyman alpha clouds at low redshift as proposed by Bahcall et al. (1996).

5. It is interesting to see whether the decay of CDM particles has consequences on the dynamics of stars in our own Galaxy. A star at a galacto-centric distance r will have an extra outward velocity $v_r = \frac{r}{M}\frac{dM}{dt}$ (this is called "K-term" in galactic dynamics), which gives $v_r = 0.4(r/10\,\mathrm{kpc})$km/s for $\tau = 1.44 t_0$ (assuming CDM and baryonic mass are equal within the relevant radius), not inconsistent with observations (e.g., Ovenden & Byl 1976).

3.5. *Tests of the* ΛDCDM Model

One clean test that could either falsify or confirm the ΛDCDM model will come from measuring the ratio of gas mass to total mass in clusters of galaxies. We predict that M_{gas}/M_{tot} should display a trend: lower at higher redshift. The ratio should be lower by 31% at $z = 1$ than at $z = 0$. This is a potentially observable signature by X-ray observations (e.g., Jones & Forman 1992) or observations of the Sunyaev-Zel'dovich (SZ) effect (e.g., Carlstrom, Joy, & Grego 1996).

Similarly, the mass-to-light ratio for galaxies, particularly dwarf galaxies, should show a trend of increasing with redshift. However, complications are expected in this regard due to much more involved astrophysical processes concerning star-formation, which is likely to be dependent on density and temperature among others. Nevertheless, attempts to try to detect this trend are worthwhile.

4. CONCLUSIONS

We have shown that, by allowing for one half of the CDM particles to decay by $z = 0$ into relativistic particles, the problem of excess small-scale power in the ΛCDM model is remedied. In essence, the decay of CDM particles results in reduction of CDM mass and expansion of the halo, and lowers the concentration of CDM in the inner region to brings the model into agreement with observations. The problem of excess number of dwarf galaxies in the ΛCDM is solved by the same mechanism but manifested in a quite different way. Instead of suppressing the number of predicted dwarf halos, we argue that these dwarf halos failed to form a sufficient amount of stars to be identified as dwarf galaxies even in our local neighborhood in the ΛDCDM model. It is important to search for these gas-rich dark galaxies in the Local Group.

The model is consistent with COBE, the local abundance of rich clusters of galaxies, the age constraint and q_0 from high-z SNe. In addition, the model provides a better fit to the recent BOOM result concerning the first Doppler peak and does not need to use any unconventional value for the Hubble constant.

A test of the model will be provided by measuring the evolution of gas fraction in clusters. The prediction is that the gas fraction should decrease with redshift and is smaller by 31% at $z = 1$ than at $z = 0$. X-ray and SZ effect observations should provide such a test.

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TABLE 1
TWO COBE AND CLUSTER-NORMALIZED ΛDCDM MODELS

Model	$\Omega_{0,CDM}$	$\Omega_{0,b}$	$\Omega_{0,r}$	λ_0	h	n	σ_8	t_0 (Gyrs)	q_0
fiducial	0.234	0.044	0.122	0.60	0.60	1.08	1.0	13.9	−0.38
high Ω_b	0.220	0.066	0.114	0.60	0.60	1.13	1.0	13.9	−0.38

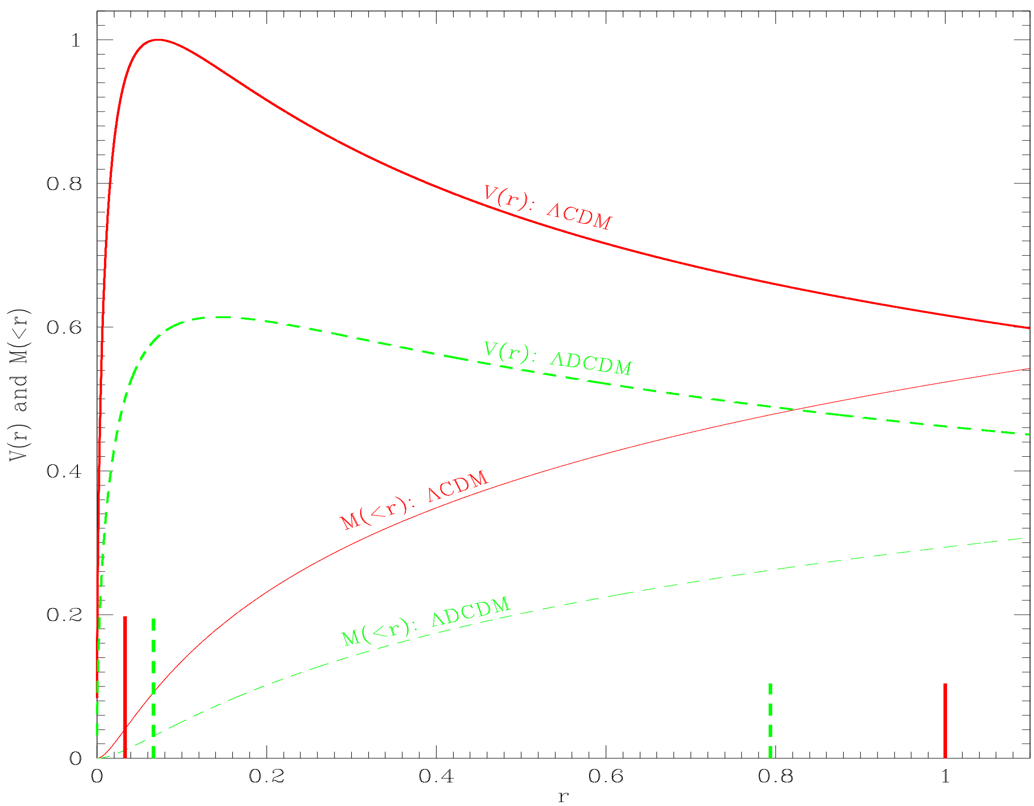

FIG. 1.— shows the rotation curves (thick) and mass profiles (thin) for the initial (solid; ΛCDM) and final (dashed; ΛDCDM) halo, both having the NFW profile but different virial radii (r_{200}). Both x and y axes have arbitrary units. The initial concentration of $c_i = 30$ is used for this illustration, although the relative effect is quite insensitive to the value of c_i. The long vertical bars indicate the core radius for the initial (ΛCDM ; solid) and final (ΛDCDM ; dashed) halo. The short vertical bars indicate the virial radius (r_{200}) for the initial (ΛCDM ; solid) and final (ΛDCDM ; dashed) halo. The final radius of maximum rotation velocity is larger than the initial radius of maximum rotation velocity by a factor of 2. The rotation velocity at virial radius is reduced by about 20% ($V_{200,f} \sim 0.8 V_{200,i}$) and the maximum rotation velocity reduced by about 40% ($V_{max,f} \sim 0.6 V_{max,i}$). The mass of a halo within a fixed proper radius in the ΛDCDM model is reduced by a factor of ~ 8.0 in the inner region and a factor of ~ 1.6 in outer region.